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CASE NO, KGP-2003-01

1   **AN ACTIVE/ADAPTIVE ACTUATOR DESIGN OF AN ADAPTIVE OPTIC MIRROR**

2   BACKGROUND OF THE INVENTION

3   Adaptive mirrors permit distorted wave fronts to be

4   reformed into undistorted wave fronts. An example of this

5   problem occurs when a plain wave front from a distant star

6   passes through the earth's atmosphere and is distorted by

7   turbulent layers of air. The heating and cooling of the

8   atmosphere by local weather effects cause these turbulent

9   layers. In general, the further the light travels through the

10   air and the denser the air is, the greater the amplitude of the

11   distortion. Adjusting a mirror surface to match this distortion

12   allows a reflected plain wave front to be observed. The

13   actuator for adjusting the mirror surface to match the wave

14   front distortion must operate very rapidly with response times

15   of one thousandth of a second or less and is called an adaptive

16   actuator. With an adaptive actuator, the adaptive mirrors

1   should perfectly match the distorted wave front laterally and

2   have half the amplitude of the wave front distortion. Another

3   kind of actuator, called an active actuator, corrects for quasi-

4   static surface errors in the mirror. Such errors may arise from

5   inadequate polishing of the mirror, the force of gravity

6   particularly as the mirror is tilted, unequal expansion of the

7   mirror as a result of temperature changes or creep in the mirror

8   surface as a result of internal strains in the mirror. The

9   adaptive mirror should perfectly match these errors.

10   The phase of the light depends on the wavelength, so the

11   shorter the wavelength the greater the phase error becomes when

12   expressed in fractions of a wavelength.

13   The actuator correction for these faults does not need to

14   have a rapid response time, but should be capable of being set

15   very accurately. The shorter the wavelength, the greater the

16   phase error and the more critical the required correction.

17   It is known in the art to use the Fried (freed) coefficient

18   as a statistical measure of the phase error. As the Fried

19   coefficient becomes smaller the distortion becomes greater.

20   As the light to be refocused moves from the infrared range

21   to the visible range, the adaptive mirror surfaces which needs

22   to be controlled to a fraction of a wavelength becomes subject

23   to even finer tuning.

1   The stiffness of a composite mirror can be calculated by

2 the structural stiffness module. The manner of this calculation

3 may be found in "Development of Lightweight Mirror Elements for

4 the Euro 50 Mirrors," by Bennett et al. Proceedings of the 2nd

5 Bäckaskog Workshop on Extremely Large Telescopes, September 11-

6 12, 2003, SPIE (in press).

7   Many piezoelectric materials are known. They have been

8 made into actuators to move or displace upon application of a

9 predetermined voltage. The voltage causes a piezoelectric

10 substance to expend or contract. For a given voltage a single

11 actuator of piezoelectric material expands in all directions.

12 Anything connected to such a device is displaced or thrown this

13 change in distance. For a given device a set throw range is

14 established. If double the throw distance is needed two

15 identical devices are placed together in electrical series

16 connections or stacked. Applied voltage must be doubled for

17 both actuators to fully respond and give double the throw

18 distance. Lateral movement in such stacks is ignored. Third,

19 fourth and more actuators are added to the stack for greater

20 throw distances.

21   For audio devices piezoelectric material is coated on a

22 sheet of metal, such as brass, steel, or other desired material

23 creating the equivalent of a bimetallic strip. In this

1 application the lateral expansion causes the device to bow to a

2 given radius of curvature for a preselected voltage and

3 thickness of the metal sheet and piezoelectric coating. In

4 general, the thinner the greater the amount of curvature or

5 bowing. These devices have been used to generate sound waves as

6 the device bows and flattens.

7 DESCRIPTION OF THE PRIOR ART

8   Adaptive mirrors have many limitations including thickness

9 of surface. If too thick the result is being unable to match

10 wave fronts having closely spread irregularities. Other

11 limitations are spacing of actuators to deform the surface and

12 inability of actuators to push with enough force to deform the

13 surface to the shape required. These are interrelated problems.

14 In general actuators have their throw distances or displacement

15 range extended by stacking piezoelectric devices in electrical

16 series connections. As the distance desired increases, the

17 voltage increases. Piezoelectric devices are made of metallic

18 plates with a piezoelectric coating and an electrical lead to

19 each so a voltage can be applied to it. A bimetallic effect can

20 be achieved in this manner to cause the device to bow.

21 Applications of this bowing have been limited to audio equipment

22 to produce sound waves.

4

1 FIELD OF THE INVENTION

2   This invention relates to a method and device to adjust the

3 active and adaptive actuator settings for an active or adaptive

4 mirror. In particular this invention relates to a device to

5 adjust for gravity induced distortion and manufacturing

6 irregularities in the polished surface as well as

7 atmospherically induced wave front distortion in the incident

8 light beam. This invention permits active problems to be

9 corrected and also allows adaptive problems to be corrected by

10 distorting the adaptive surface to correct for wave front

11 distortion in an incoming wave front.

12   This invention further relates to actuators with relatively

13 large throw distances. In particular this invention relates to

14 actuators with short response times and relatively large throw

15 distances at low voltage. This invention also relates to

16 devices that provide tens of micrometers of throw distance

17 without using stacked actuators.

18   BRIEF DESCRIPTION OF DRAWINGS

19   FIG. 1 is cutaway perspective view of the present

20 invention.

21   FIG. 2 is an exploded view of the present invention.

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1   FIG. 3 shows a unique actuator that will work with the

2 present invention.

3   FIG. 4 is a diagram showing the accuracy in displacement

4 control for the active actuator part of the subject of the

5 present invention.

6   FIG. 5 is a graph of displacement versus micrometer setting

7 for an embodiment of the present invention.

8   FIG. 6 is a cross section showing the design of the

9 piezoelectric actuator disks to maximize actuator throw.

10   DESCRIPTION OF THE PREFERRED EMBODIMENT

11   Fig. 1 is a cutaway perspective view of an active actuator

12 plus an adaptive actuator. A holding plate 10 has a plurality

13 of openings 12 as shown. The number of openings 12 is

14 determined as described below. In each opening 12, an actuator

15 14 is mounted. Each actuator 14 is mounted via a differential

16 thread arrangement described further on. Connected to each

17 actuator 14 is a push-pull rod 16 which is in two pieces for the

18 embodiment shown in Fig. 1. One piece is mounted above actuator

19 14 and the other is mounted beneath actuator 14. Electrical

20 leads 18 permit electrical signals to be sent to actuator 14

21 which can be any suitable fast response actuator, such as

22 piezoelectric crystals. Actuator 14 is an adaptive optic

6

1 actuator that rapidly becomes thicker or thinner as desired. In

2 turn this moves push-pull rods 16 back and forth. Its design is

3 shown in Fig. 4 and will be described further on. One end of

4 the push-pull rod has a mounting 20 which is fastened to the

5 back of an adaptive optic mirror 22. Push-pull rods 16 and

6 mount 20 may be connected to each other by gluing a threaded

7 foot to mount 20 and threading a small screw both into it and

8 into rod 16. Other methods of attachment may be used. In a

9 similar fashion push-pull rods 16 may be glued to actuator 14

10 and mount 20 is glued to the back side of adaptive mirror 22.

11 The screws keep the actuator function in line with the normal to

12 the object being displaced.

13   Holding plate 10 is mounted in case 24 shown in a cutaway

14 view. Screws 26 may be used to keep holding plate 10 rigidly

15 mounted. Other methods of attachment may be used as desired.

16 Adaptive mirror 22 may be glued to case 24 or held in place by

17 being attached to mounts 20.

18   Adaptive mirror 22 has a predetermined coefficient of

19 thermal expansion. To avoid thermal stress to the mirror, case

20 24 should have the same coefficient of thermal expansion as well

21 as holding plate 10. An example of suitable material is a

22 cyanate ester composite. Another material that appears suitable

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1   is a carbon-silicon carbon material available as CSIC on the

2   commercial market.

3   An actuator may be made of a thin metal sheet coated with a

4   piezoelectric coating. This is a form of bimetallic strip. A

5   bimetallic strip is made of two metals having different

6   expansion coefficients. They are often used to make contact when

7   the temperature in a room changes, for example. By allowing a

8   relatively large area of two thin sheets to bend when the

9   dissimilar expansion coefficients expand one sheet relative to

10   the other one gets a tremendous magnification of motion compared

11   to the motion involved in letting one material expand normal to

12   its surface. For example, in a commercial 6.5" diameter adaptive

13   optic mirror made up of 37 piezoelectric stacks spaced 1.1"

14   apart the sensitivity of each stack was 55 Å/volt displacement.

15   It required 1.5 kV to move the mirror surface by 8 μm and the

16   bandwidth was DC to 300 Hz. Compare that to the double sandwich

17   described here, where the throw is approximately one μm/volt and

18   a bandwidth of DC to 2.5 kHz. The high voltages required have

19   always been a problem with piezoelectric actuators and

20   voltage-wise the present invention represents a gain of 1

21   μ/0.0055 μm /volt = 182 times greater for the present system.

22   Actuator 14 may be made of one or two of these actuators, say 19

23   millimeter in diameter, each separated by a 1.6 millimeter thick

1 insulating ring, and mounted back to back to maximize throw

2 distance for minimum voltage. Examples of usable actuators are

3 ones with a throw distance of ±30 micrometers at 60 V applied

4 with a reaction time of less than a millisecond. If only one

5 plate is used, the throw distance is reduced by a factor of 2.

6 If a conventional piezoelectric stack is used, typically the

7 reaction time as compared to the two plate actuator 14 is

8 increased from 0.4 msec to 3.3 msec (milliseconds) nearly an

9 order of magnitude.

10 Fig. 2 is an exploded view of the setting mechanism. In

11 Fig. 2, push-pull rod 16 is shown mounted in actuator holder 28,

12 which in turn is within differential thread 30 which in turn is

13 within support collar 32. A two-part adjustment handle having

14 coarse handle 34 and fine handle 36 may be made of brass or

15 other metal or equivalent substance. Likewise both may have a

16 knurled surface 38 or a portion thereof as shown. Texturing is

17 not part of the invention but is known as a convenience for such

18 surfaces. Coarse handle 34 is cylindrical and hollow along its

19 intended axis of rotation. Coarse handle 34 has two portions of

20 differing outer diameters so a surface 40 is formed. Surface 40

21 has the larger of the two outer diameters and is set to be

22 greater than the diameter of openings 42 in calibration mounting

23 plate 44 as shown in Fig. 1. The use of terms coarse and fine

1   is subjective and can be reversed. These two handles serve as a

2   first and as a second adjustment handles.

3   Referring back to Fig. 1, calibration mounting plate 44 is

4   rigidly mounted in case 24 by screw 46 or any other holding

5   means. A plurality of openings 42 are placed in mounting plate

6   44 one each which is axially aligned with openings 12 in holding

7   plate 10. Again matching coefficients of thermal expansion is

8   recommended for the material used to make mounting plate 44.

9   Extension 48 is the portion of coarse handle 34 that fits

10   through calibration mounting plate 44 until surface 40 is flush

11   with calibration mounting plate 44. The length of extension 48

12   is such that it becomes flush to support collar 32 when fully

13   inserted through calibration mounting plate 44. On the end of

14   extension 48 at least one tab 50 is placed which fits notches 52

15   on support collar 32. In Fig. 2 two tabs 50 are shown. This

16   number may vary. Tabs 50 extend the length of extension 48 and

17   prevent a flush fit unless they fit into matching notches 52

18   placed in support collar 32. When tabs 50 are inserted into

19   notches 52, support collar 32 may by screwed up and down within

20   holding plate 10 by coarse handle 34. Fine handle 36 has an

21   extension 54 whose outer diameter allows it to fit within the

22   hollow portion of coarse handle 34. Extension 54 has a smaller

23   outer diameter than the rest of fine handle 36, which creates a

1 surface 56, which fits flush to coarse handle 34 when extension

2 54 is inserted into coarse handle 34. The length of extension

3 54 is set so it is flush to actuator holder 28 except for a tab

4 58 which fits into a corresponding notch on the opposite side of

5 actuator holder 28 from the side in contact holding push-pull

6 rod 16. When fine control 36 is turned, extension 54 via tab 58

7 screws actuator holder 28 back and forth within support collar

8 32. Support collar 32 may not move because tab 50 of coarse

9 handle 34 do not permit it to turn except when coarse handle 34

10 is intentionally turned. Likewise, fine control 36 prevents

11 actuator holder 28 from turning when support collar 32 is moved

12 by coarse handle 34. The depth of tabs 50 and 58 set the limit

13 of adjustment distance that actuator 14 can be moved. For

14 micrometer distance adjustments tab depths of millimeters give a

15 reasonable safety range. Because coarse handle 34 and fine

16 handle 36 slide through openings 42 to make a flush fit without

17 attachment, one calibration setting mechanism may be used to set

18 each actuator 14.

19   Fig. 3 shows an assembled view of Fig. 2 and an alternate

20 embodiment if loss of adjustment control is a concern. In Fig.

21 2 embodiment support collar 32 must be allowed to turn within

22 the opening it is inserted into. If support collar 32 is

23 rigidly fixed in that same opening the technique to adjust may

11

1   be varied. To fix support collar 32 in a manner so it cannot

2   twist, it may be glued or have a ridge machined onto it to fit a

3   matching slot. Any known method of making a nontwist mount will

4   work. In the prior embodiment, differential thread 30 was moved

5   as support collar 32 was turned. Since support collar 32 is not

6   allowed to turn in this embodiment, for example, a ridge 33 is

7   added to fit a notch 13 as shown in Fig. 1. The effect of ridge

8   33 within notch 13 is to hold support collar 32 so it cannot

9   turn. Differential thread 31 is rigidly mounted to coarse

10 adjustment handle 35. Within differential thread 31 is

11 threadably inserted fine adjustment handle 37 which includes a

12 threaded end 39 to which is mounted a push-pull rod 16, not

13 shown. This embodiment allows as much distance to adjust as

14 desired. Because it is rigidly mounted to push-pull rod 16 and

15 actuator 14 this calibration mechanism must have one per each

16 actuator and may cause crowded conditions behind mounting plate

17 44.

18   Fig. 4 shows an actuator 14 with push-pull rod 16 mounted

19 between actuator holder 28 and adaptive mirror 52. Push-pull

20 rod 16 may be glued on or otherwise rigidly fixed to both

21 actuator holder 28 and adaptive mirror 52. As shown, actuator

22 holder 28 has threads 60 and a notch 62, which fits tab 58

23 previously shown.

12

In the preferred embodiment push-pull rod 16 is split into
two segments separated by piezoelectrical plates 64 connected at
the edges. As shown two piezoelectrical plates 64 are mounted
back to back to a buffer material 66. Piezoelectric plates 64
may be commercially available models such as KBT-33-RB-2CN,
KBT-33-RB-2S, KBT-XXRB-2SC/N, or KBS-35DA-3A, all offered by
Kyocera. In general a piezoelectric plate is a metal plate such
as brass, stainless steel or so formed with a piezoelectric
coating. Electrical leads are connected to each in the known
fashion. When a voltage is applied to them the piezoelectric
plate expands laterally and bows causing the displacement to
increase. The displacement resulting from the bowing is much
greater than the vertical expansion normal to the plate surface
as described above. Also the larger the area of the metal plate
that is coated, the more the displacement because a bigger
surface is warping. This means that in addition to greater
voltages greater areas per actuator can be required. The
present invention provided 30 μm vertical displacement for low
voltage of the metal plate, which is about .004 inch thick, and
the diameter of the plate is no greater than the influence
function of the faceplate of the mirror to be adapted. Plates
64 may be glued to material 66 and to push-pull rod 16 segments
as shown. Any glue that does not shrink as it dries is

13

1 appropriate. Glues that shrink will warp the thin optical

2 surface as they dry and are inappropriate for this design.

3 Buffer material 66 ideally may be a silicon rubber ring between

4 plates 58. Use of a rubber ring will work for material 66 with

5 the added advantage of allowing space for plates 58 to bow

6 inward towards each other. Electrical leads 18 are connected to

7 a voltage source as desired to cause plates 58 to expand or

8 contract. A cross section of this preferred embodiment is shown

9 in Fig. 6.

10 For high quality control of adaptive optic mirrors, the

11 final polished surface may still have a surface contour that

12 effects performance. Such contours can be observed via

13 interference fringes and the local areas that are too high or

14 too low identified. Installation of the mirror surface and

15 connection of the plurality of actuators 14 to the backside of

16 adaptive optic mirror 52 may also induce surface distortions.

17 By systematically inserting the coarse and fine handles through

18 calibration mounting plate 44 each actuator 14 may be screwed in

19 the direction needed to level adaptive optic mirror 52 surface

20 at that location. Once the surface distortion is removed using

21 active optics, the applied voltage to each actuator 14 will, if

22 mirror surface 52 is thin enough to have a short influence

23 function, distort adaptive optic mirror surface 52 in the

1   direction and amount of displacement necessary to correct for an

2   incoming distorted wave front.

3   Various combinations of threads may be used between coarse

4   control and fine control. To date the best combination of

5   threads has been found to be 1/2-20 SAE and a M8-1.25 metric

6   screw. The matching threads should be as long as possible

7   without binding and the threads themselves as deep as possible

8   to provide maximum contact. An example is to use 1/2-20 SAE

9   threads, which have a half-inch diameter, for this purpose. The

10   thick heavy rod also helps to keep the screws from being bent

11   internally, which introduces a systematic error into the

12   measurements.

13   Fig. 5 shows the surface displacement in micrometers, μm,

14   for a turn of eight graduation on a fine adjustment micrometer,

15   which has 100 graduations per turn. This data is for the above

16   combination of threads.

17   Fig. 6 is a cross section of the preferred actuator for the

18   present invention. By having plates 64 in parallel with the

19   piezoelectric layers facing each other and separated, the throw

20   distance is twice the bowing of a single plate. In Fig. 6, each

21   plate 64 is free to bend like a bimetallic strip and much

22   further throw distance is achieved than if only the vertical

23   expansion of the plate has an effect, as in a conventional

1 piezoelectric stack. For the same voltage, the throw distance

2 increases by a factor of 2 compared to that of a single plate

3 and 182 times that achieved per volt for a conventional

4 piezoelectric stack. Throws of 140 μm have been achieved at

5 higher voltage, but normally 30 μm is all that is needed for an

6 adaptive optic application. In practice 30 μm throw distances

7 have been achieved at 30 volts. It is to be noted that the

8 device works with a single plate 64 as the actuator. Use of two

9 electrically in parallel doubles the effect without increasing

10 the voltage. The size of the throw distance depends on the

11 thickness of the actuator materials and the surface area. The

12 thicker the less bending and the greater the surface area the

13 larger the bending. For the application shown, surface area

14 should be comparable to the influence factor of the mirror

15 surface.